Muon beam production

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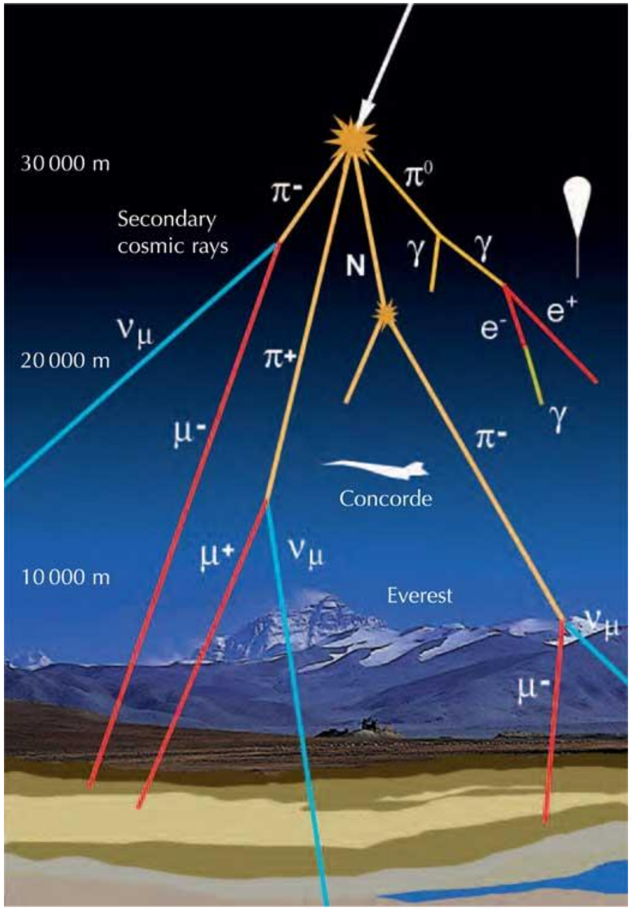
Outline

- Fermilab accelerator complex
- Beam delivery to Muon Campus
- Bunch formation and targeting
- Target material, products and selection
- Beam distribution after target

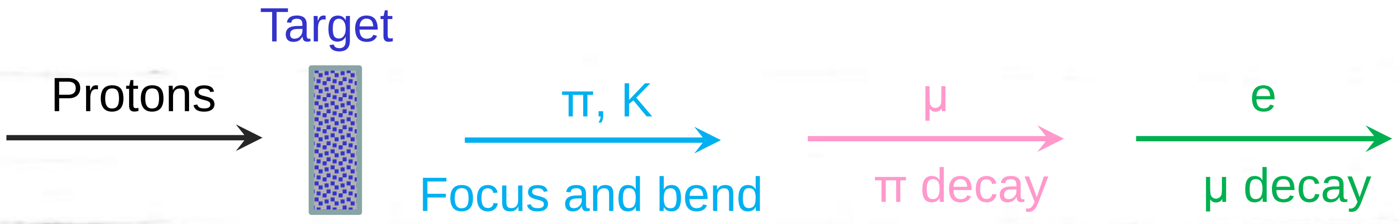
Muon production

- Atmospheric muon beam
  - High energy protons strike atmosphere
  - Pions and kaons are produced
  - Pions decay before they interact
  - Muons are born
  - Arrive at sea level with a flux of ~ 1 muon per square cm per minute
- Unfortunately, these muons are not good enough for measuring g-2



Creating a "human-made" muon beam

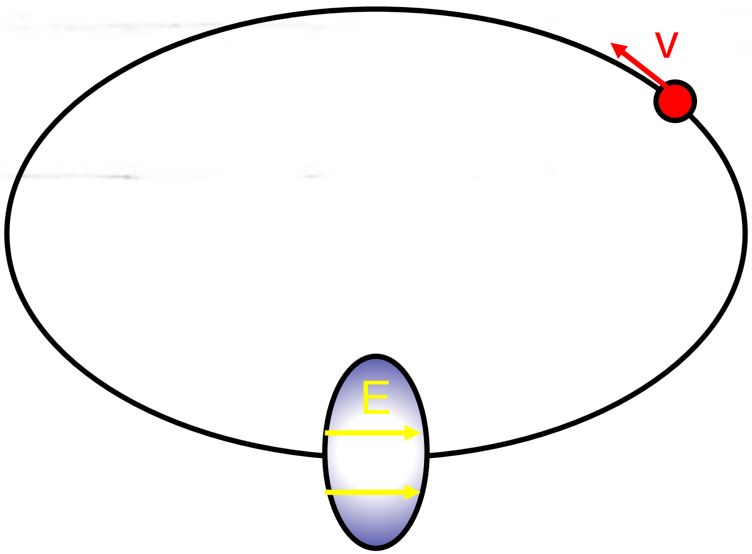
- Measuring g-2 is only possible using high-energy accelerators wherein high-intensity muon beams can be generated
- Major production components:
  - Proton beam
  - Pion production target
  - Focusing and energy selection system
  - Decay and muon transport region
  - Muon decay region

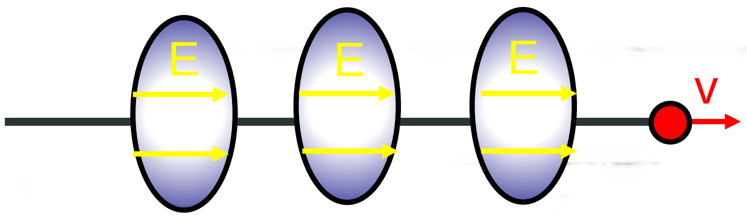


Fermilab accelerator complex

- Consists of a chain of stages in order to reach high-energies

Types of accelerators

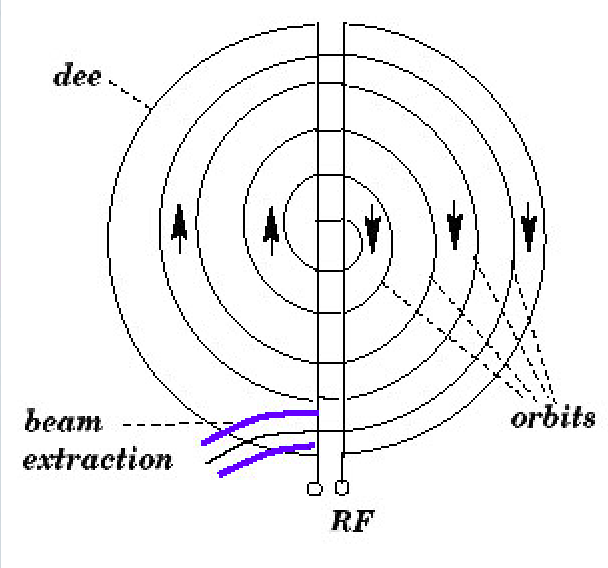




- Circular accelerators
  - Repeated passage of beams via a series of cavities
  - Suitable for heavy particles, i.e. protons
- Linear accelerators (linac)
  - Particles pass only once through each cavity
  - Suitable for light particles, i.e. electrons

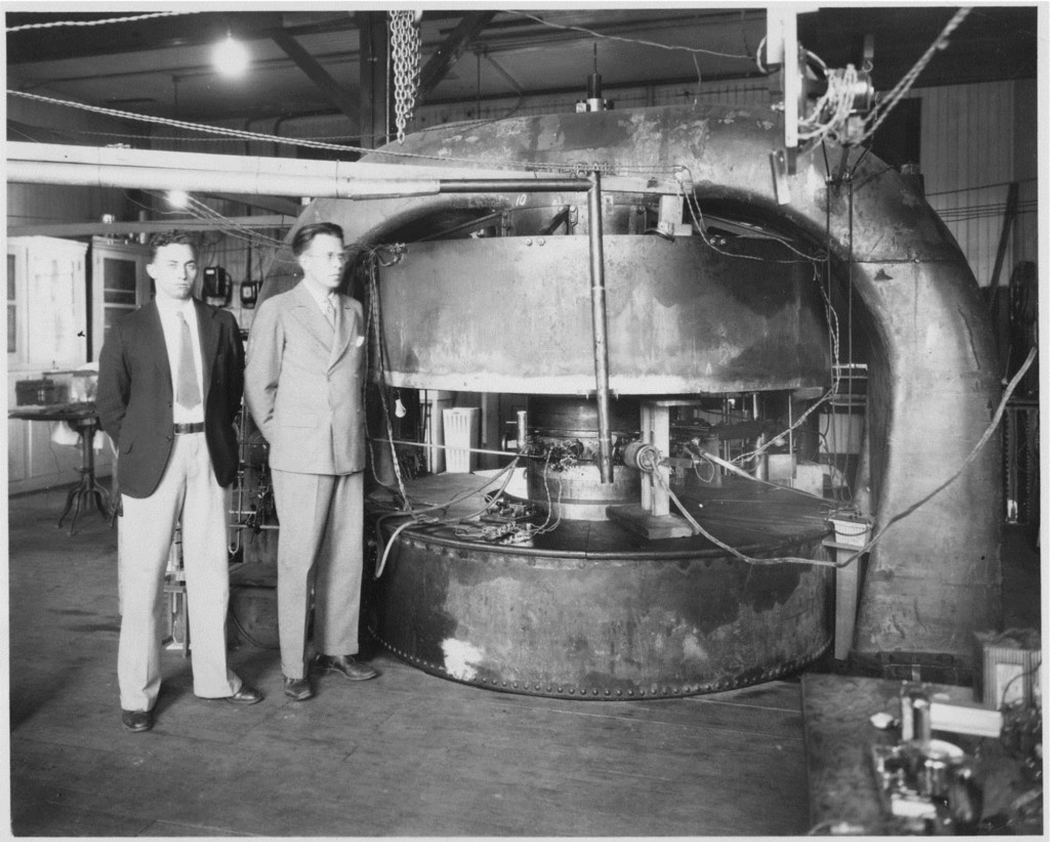
Circular accelerators - Cyclotron

Cyclotron



- Uniform circular motion is maintained via centripetal acceleration: $\frac{mv^2}{r} = qvB$
- Radius is $r = \frac{mv}{qB}$
- Revolution frequency: $\omega = \frac{qB}{m}$
- The driving RF at the gap does not depend on the momentum in the classic limit
- Limited to low energy applications (~100 MeV)

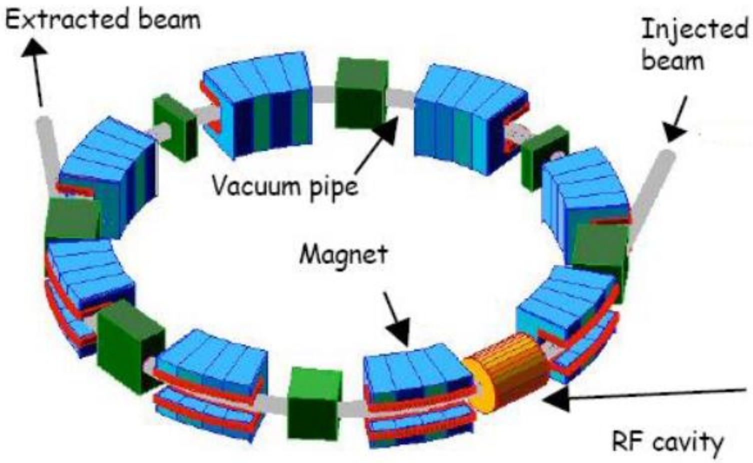
Circular accelerators - Cyclotron



- Invented by Ernest O. Lawrence in 1929 at UC, Berkeley

Circular accelerators - Synchrotron

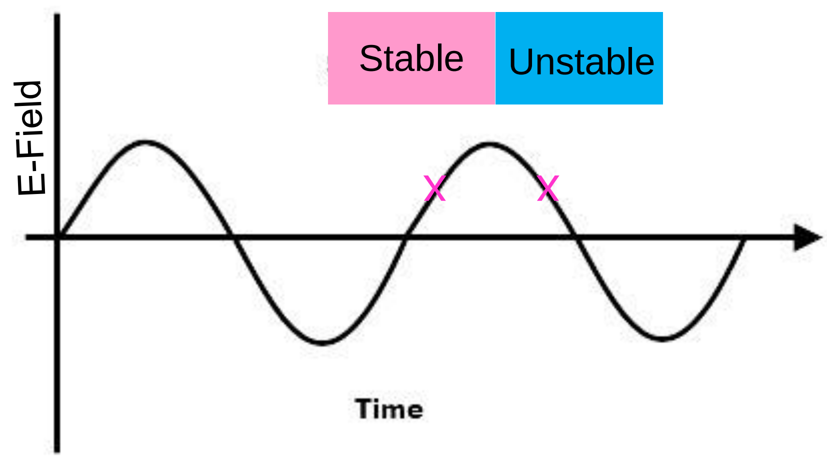
Synchrotrons



- Start with the cyclotron idea and note that: $p = qBr$ and $\omega = qB/m\gamma$
- Particles are accelerated in a circular orbit were the bending B-field & rf frequency increase with time so that a constant orbit is maintained
- The concept of rf cavities will be discussed next

Acceleration (1)

- Principle: Particle exchanges energy with a wave



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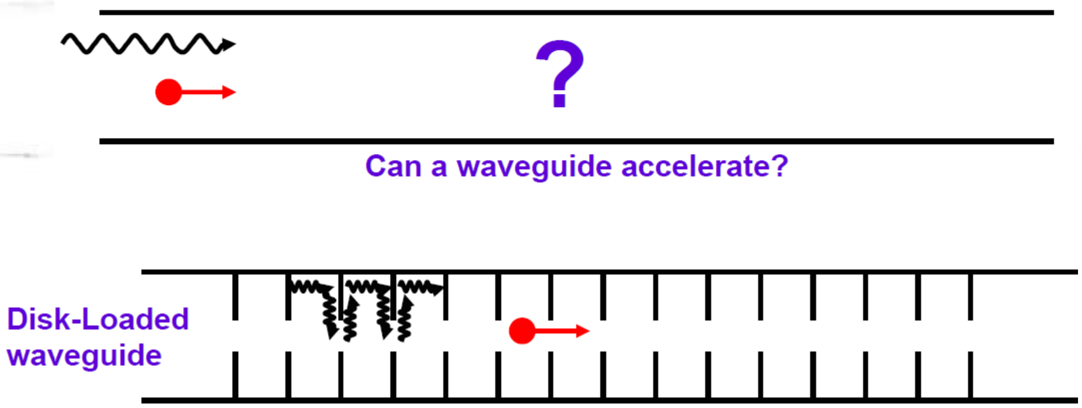
Acceleration (2)



- Phase velocity in the waveguide is greater than the speed of light
- Unless we do something, particle will quickly lose synchronicity with the wave
- A disk loaded waveguide can be constructed to “slow-down” the phase velocity

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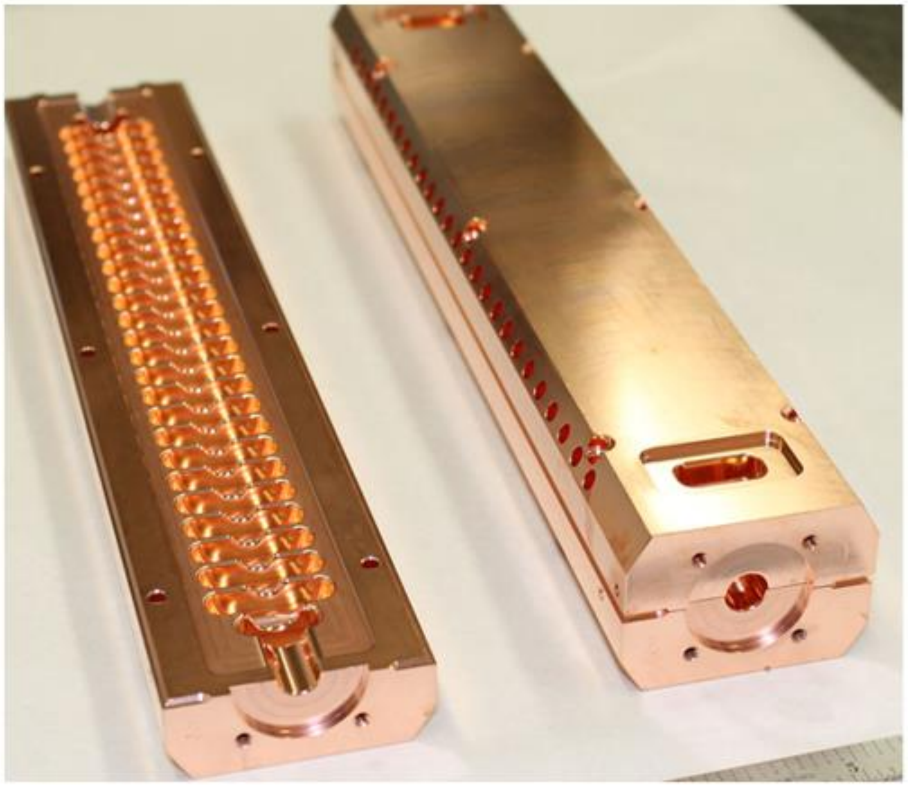
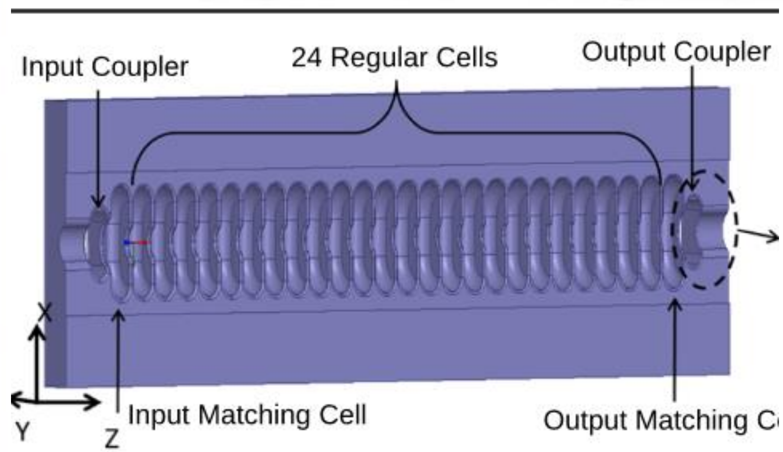
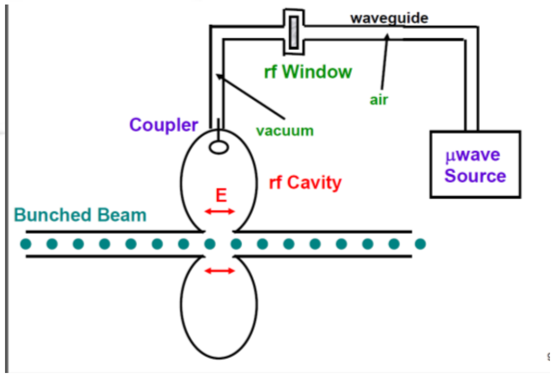
Example

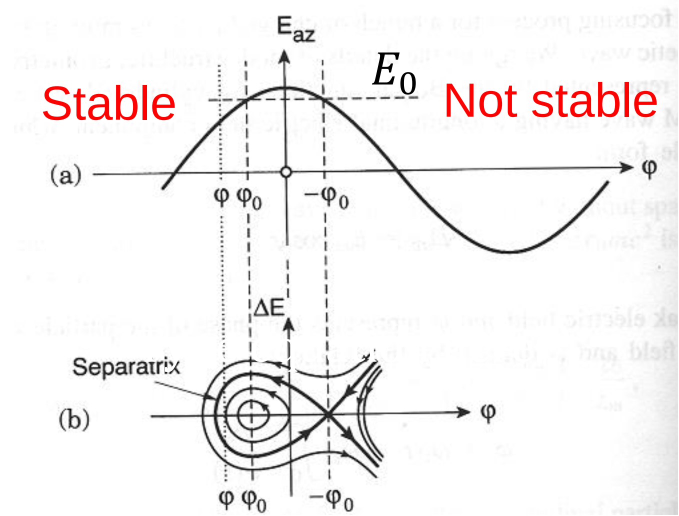




- Example: CLIC prototype cavity 11.994 GHz cavity (details: Argyropoulos et al. PRAB 21, 061001 (2018)

Acceleration stability





- Cavity is set up so that the particle at the center of the bunch (E_0, φ_0) acquires the right amount of energy
- Particles arriving in nearby phase and energy will oscillate about this ideal position
- RF system acts as a stabilizer keeping the particles within tight bunches around the synchronous particles

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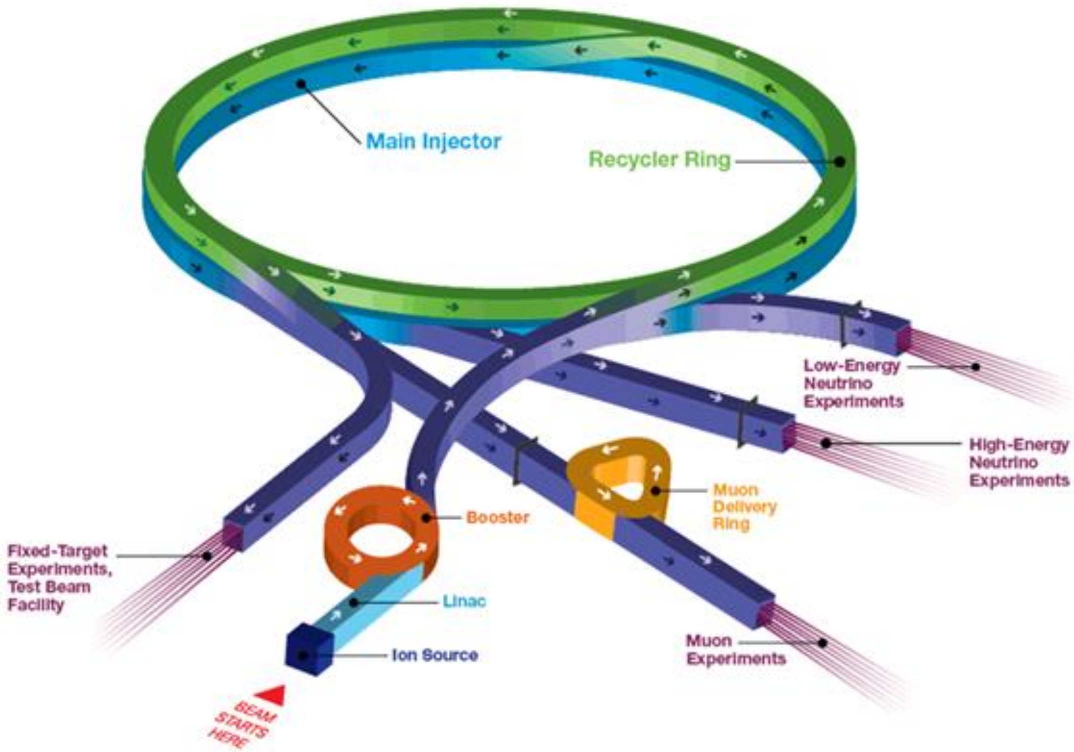
Fermilab accelerator stages



ION SOURCE

↓

LINAC
(150 m)

↓ 400 MeV

BOOSTER SYNCHROTRON
(475 m)

↓ 8 GeV

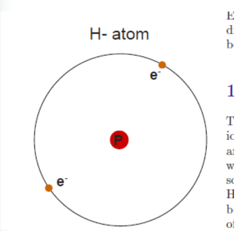
RECYCLER
(3300 m)

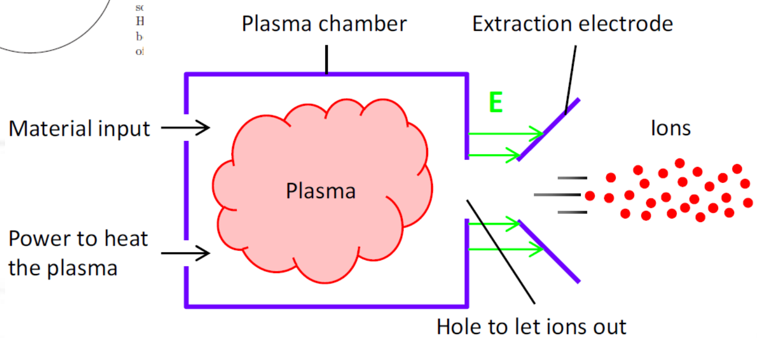
↓ 8 GeV

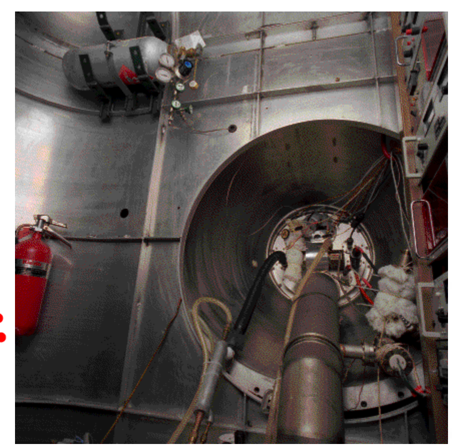
MUON CAMPUS
(~3000 m)

Step 1: Fermilab ion source

- An ion has a charge, which means that E & B-fields apply strong forces to them and therefore can be accelerated
  - Lorentz Force: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
- An ion source typically consists of a plasma generator and an extraction system
- Fermilab's ion source creates H-

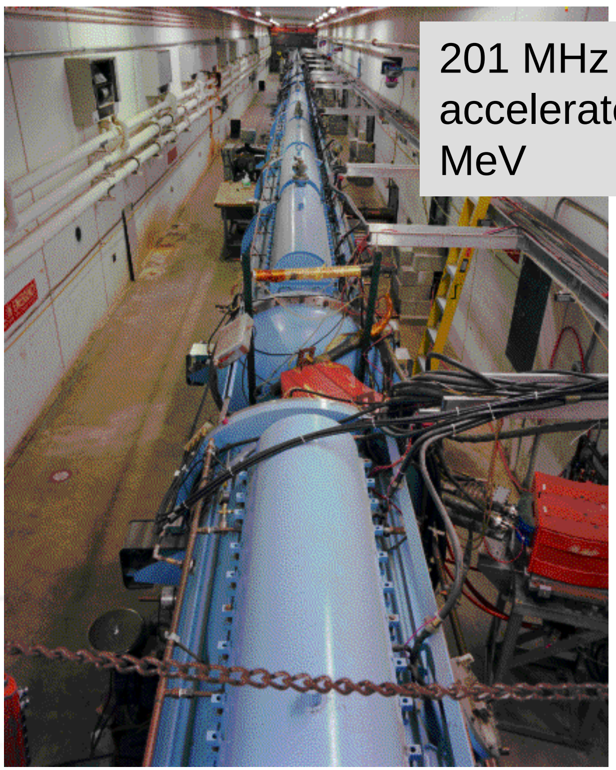






Step 2: Fermilab Linac

- Fermilab linac is a linear accelerator which uses many accelerating cavities through which the particle passes only once



201 MHz cavities, accelerate to 116 MeV

Following 805 MHz cavities, accelerate to 400 MeV

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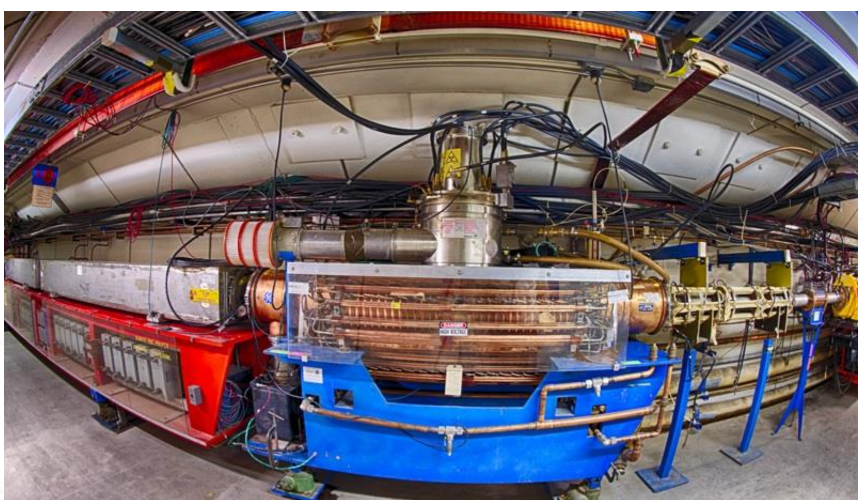
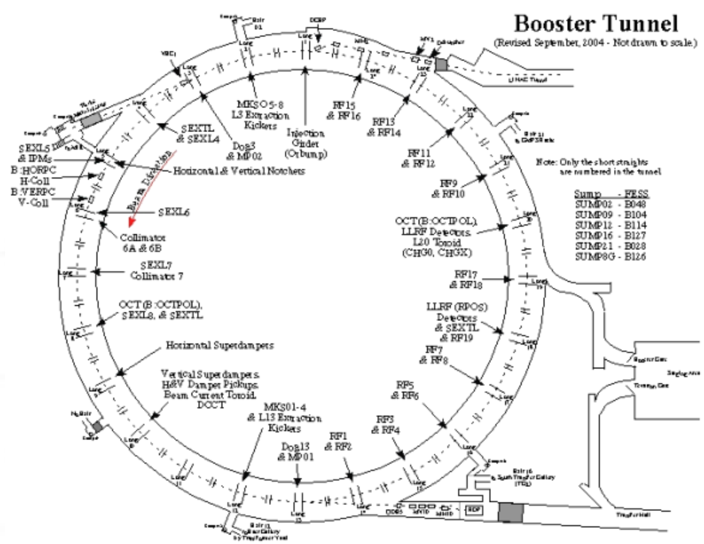
Step 3: Fermilab booster synchrotron

- Fermilab booster accelerates a proton beam from 400 MeV to 8 GeV in less than 67 ms
- RF system sweeps its frequency in the range 37.8 → 52.8 MHz during acceleration
- Booster captures the protons into 81, 53 MHz bunches (1 batch). Each batch is 1500 ns long and contains 4×10^{12} protons

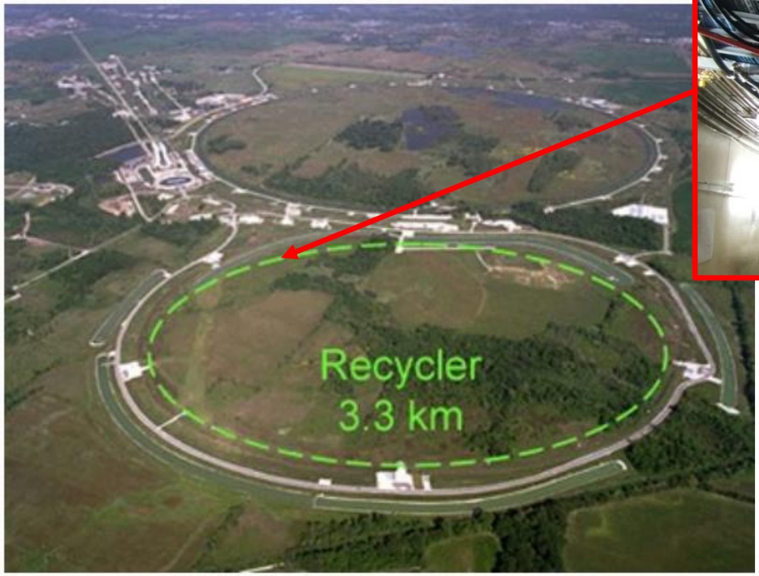




Step 4: Recycler Ring (RR)

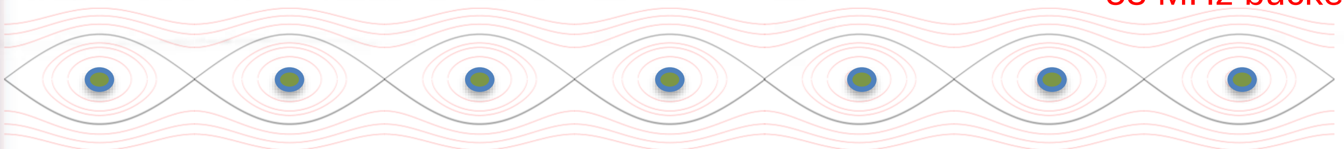
- The batch entering the recycler is not appropriate for g-2
  - Very long (occupies 1/7 of the Recycler)
  - Very intense (problem for g-2 instrumentation)
- Solution: Bunch re-formation

4 x 2.5 MHz RF cavities

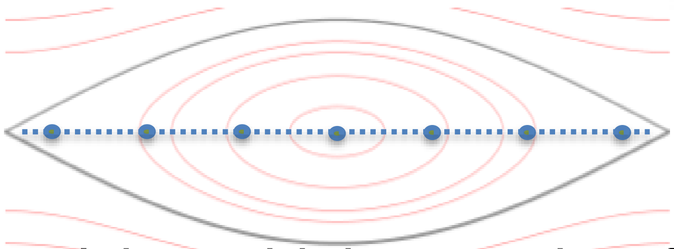


Bunch coalescing (1)

53 MHz buckets in recycler (1 batch)

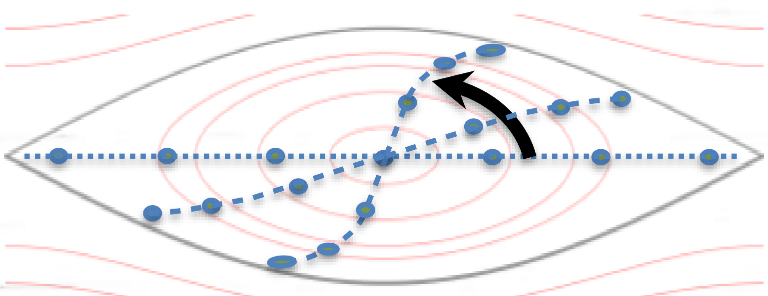


- Using four separate 2.5 MHz cavities the 81 bunches from the booster are divided into four 21-bunch segments



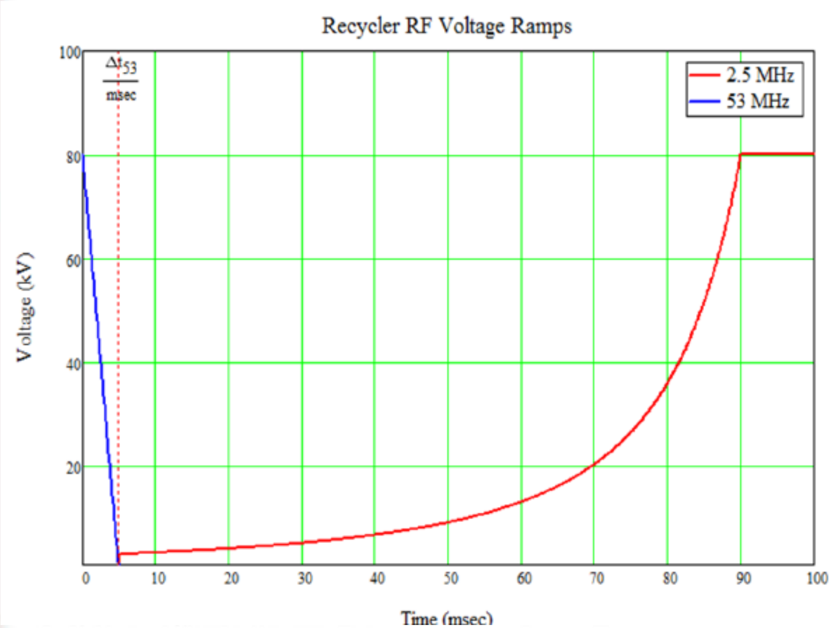
53 MHz RR system OFF. 2.5 MHz ON. Beam is rebunched into four 2.5 MHz bunches

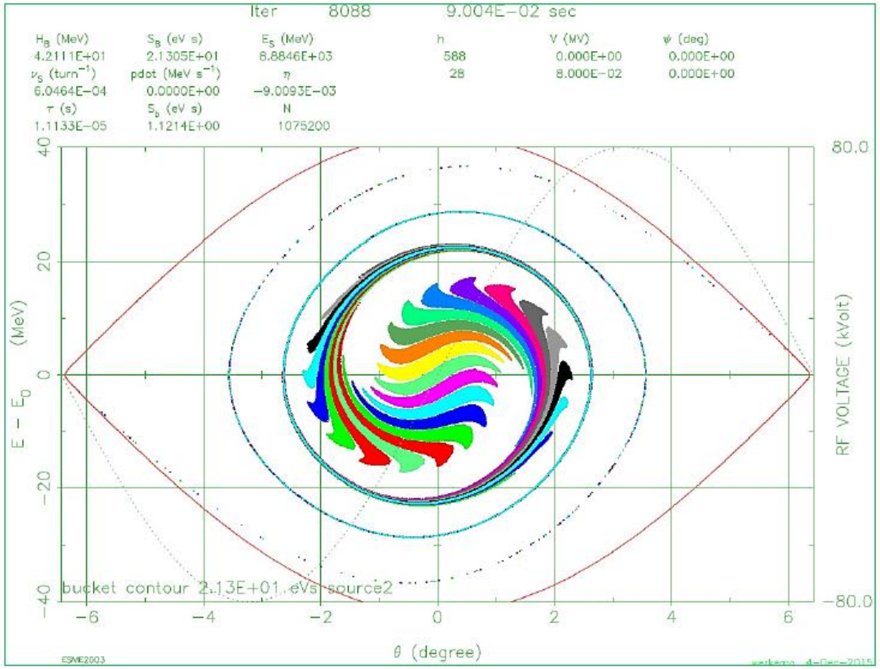
- Then by applying a high enough voltage the 21 bunches rotate in longitudinal phase-space and acquire a shorter time span



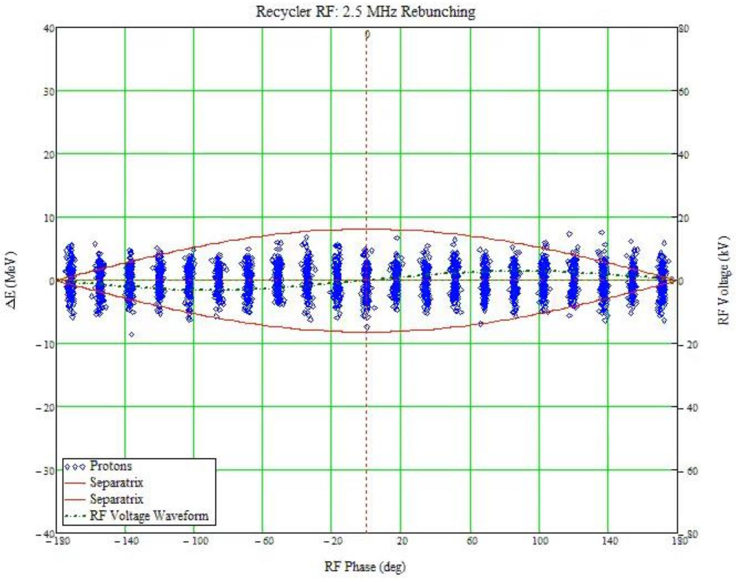
Progressively increase voltage of the 2.5 MHz RF system

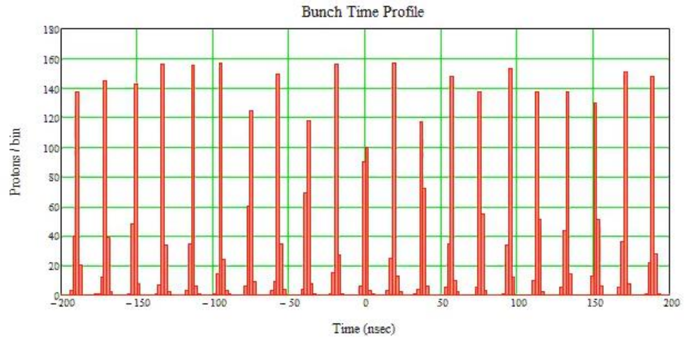
Bunch coalescing (2)





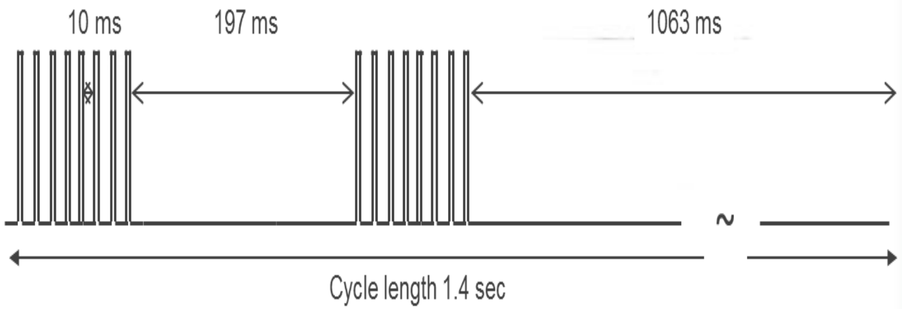
Beam parameters for Muon Campus





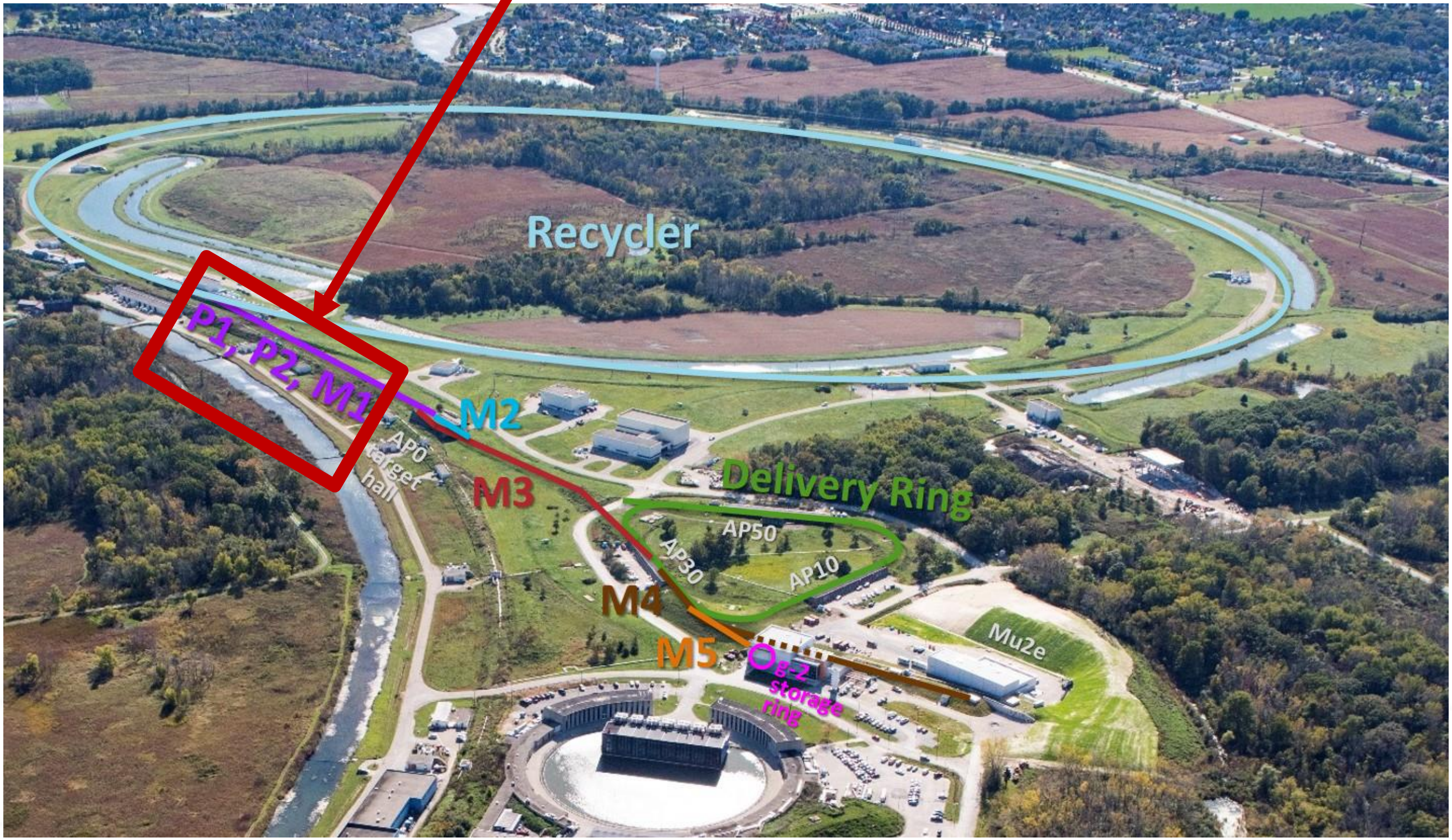
Created by: Steve Werkema (Fermilab)

- 4 Booster batches every 1.4s rebunched into 4 new bunches each

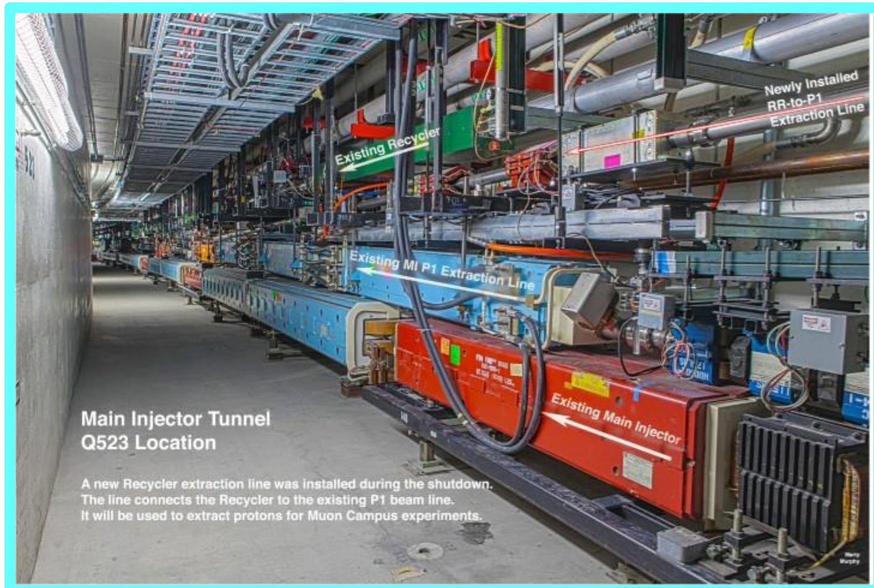


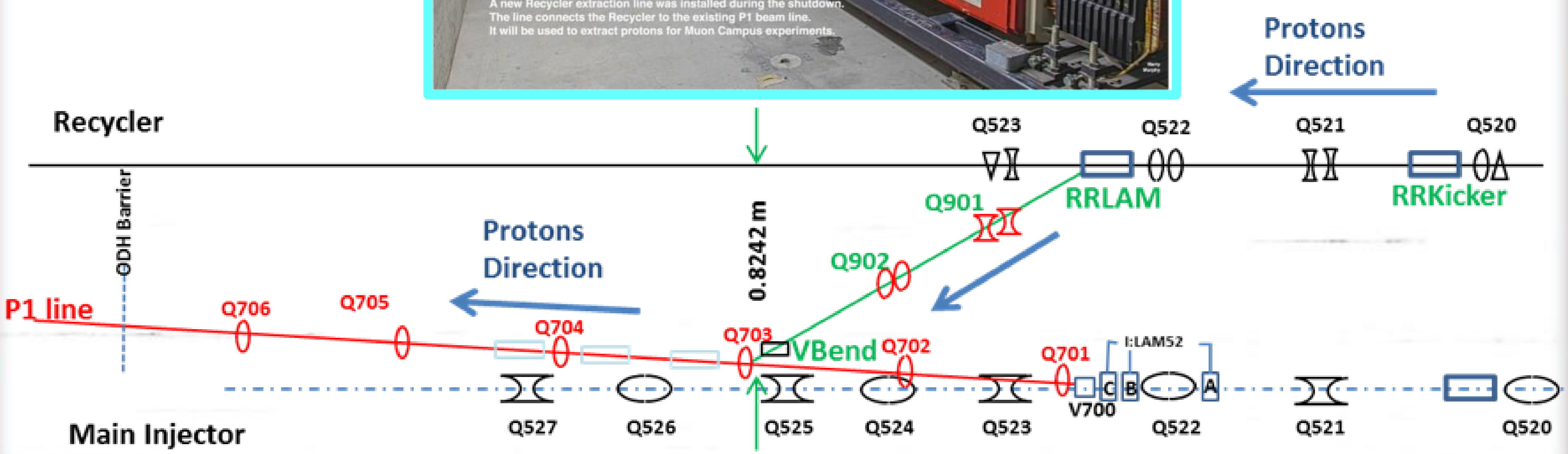
Parameter	Value
Protons on target (POT) per pulse	10^{12}
Pulse width	120 ns
Number of pulses	16
Cycle length	1.4 s
Frequency	12 Hz
Primary beam kinetic energy	8 GeV

RR to target line

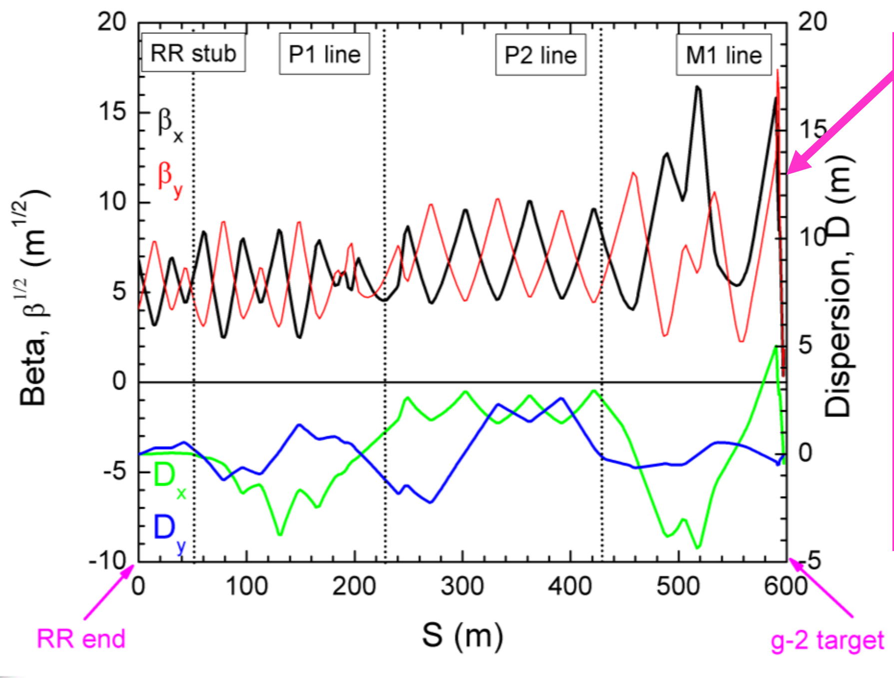


Directing protons is not trivial…



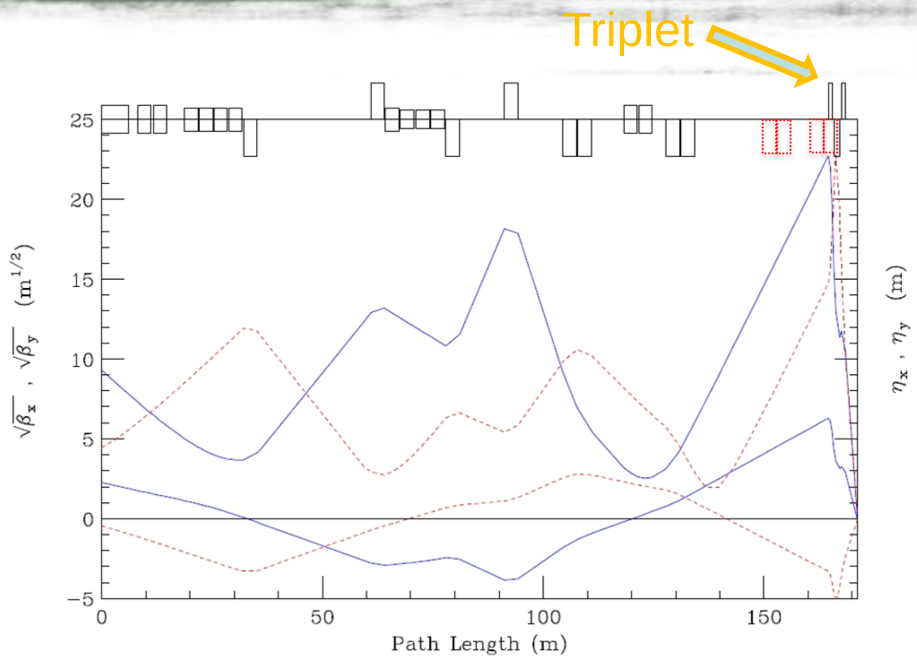


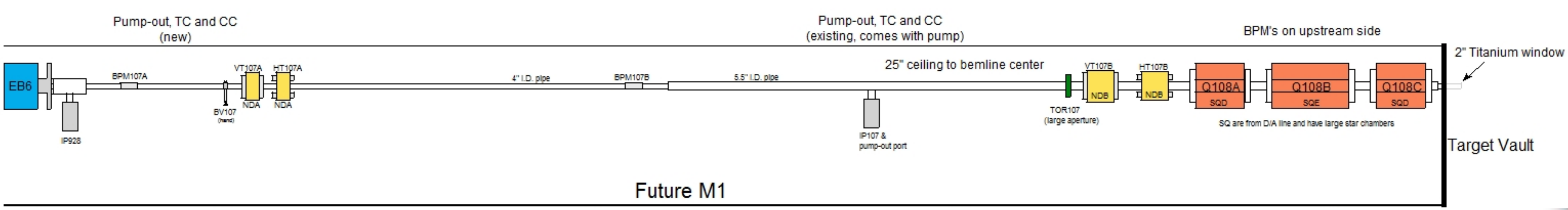
Final focus



- spot size on target: 0.15mm
- Assuming $\varepsilon = 1.5$ mm.mrad (unormalized, 95%), then $\beta = \frac{\sigma^2}{\epsilon} = \frac{0.15^2}{1.5x10^{-3}}\,\text{mm}$ =0.09 m!
- Requires good beam control & large beta's upstream

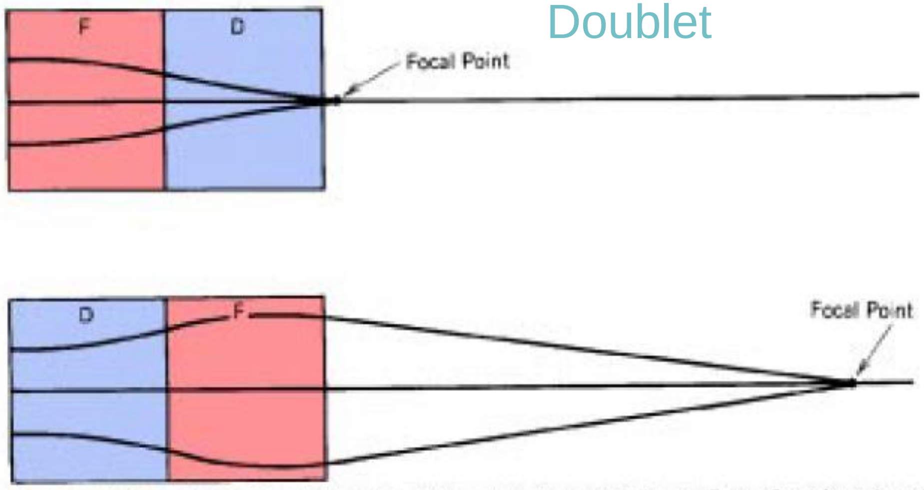
Quadrupole triplet for the g-2 target



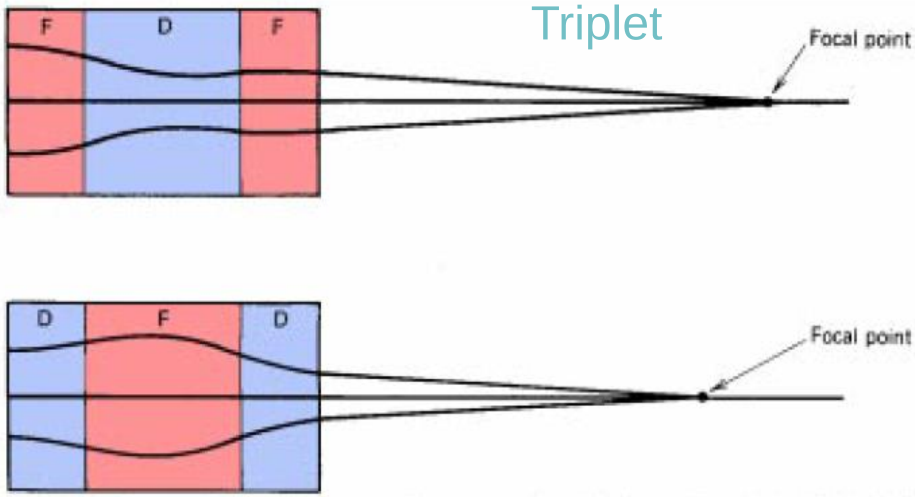


Final focus with a quadrupole triplet

Doublet



Triplet

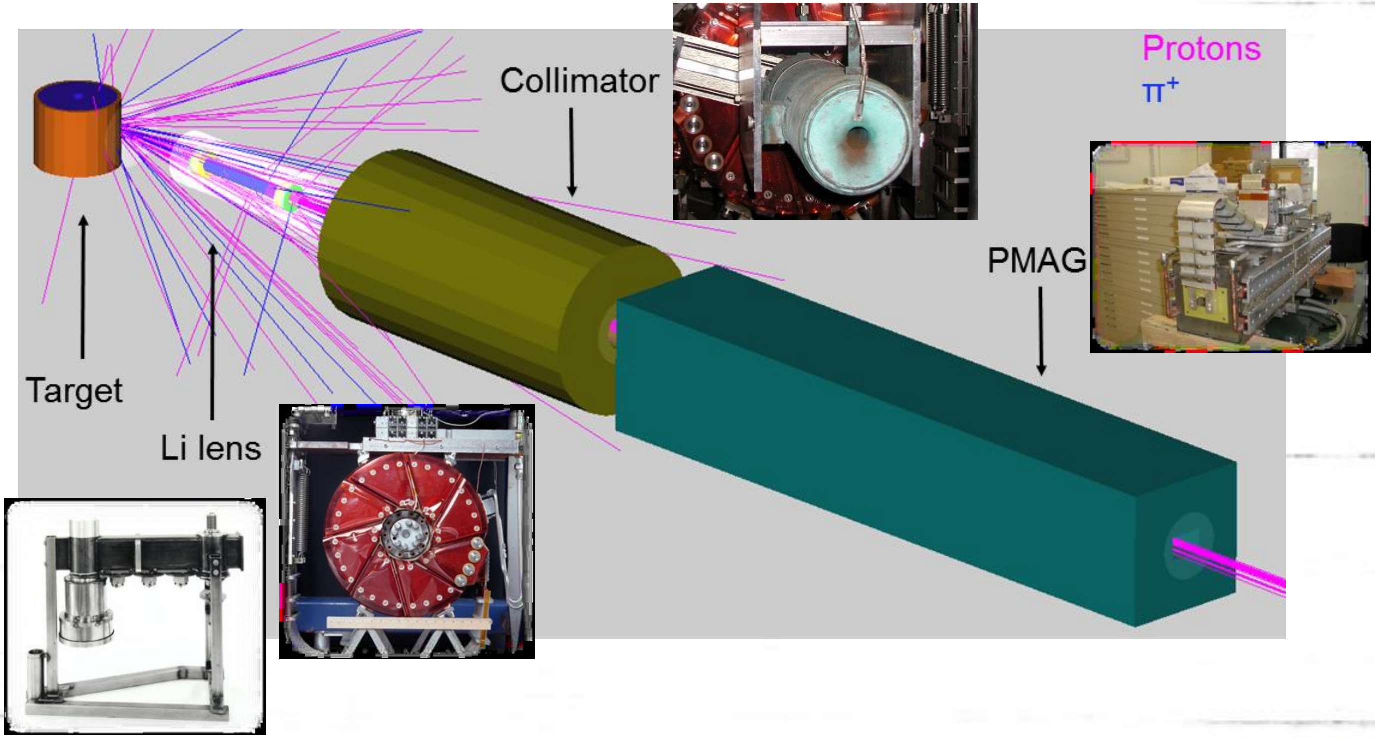


- Combination of equal D and F quads leads to net focusing
- BUT focusing is different in x and y directions

- A quad triplet focuses equally in both directions and thus focus to a point
- Allows stronger focusing
- Ideal for small spot sizes

Target station

- Target station consists of five devices: production target, lithium lens, collimator, pulsed selection magnet & dump
- Muons are produced indirectly: p$\rightarrow\pi^+$ (26 ns)$\rightarrow\mu^+$ (2 μs)

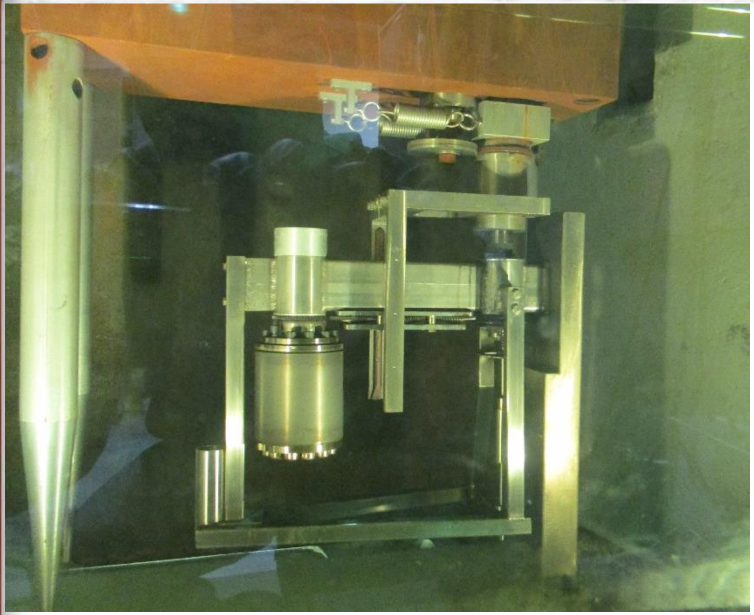


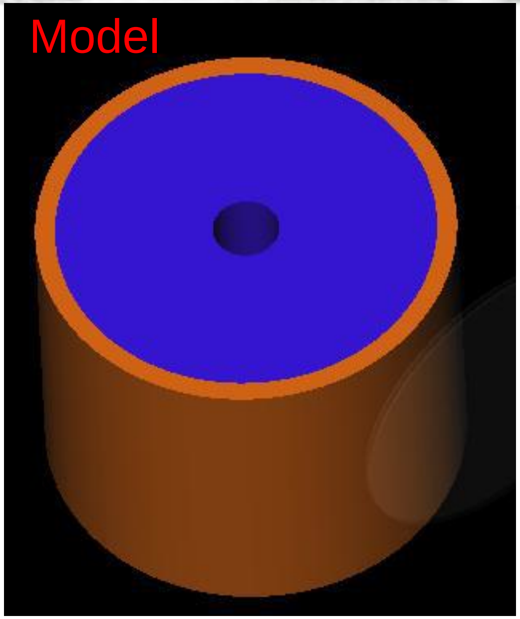
Target considerations

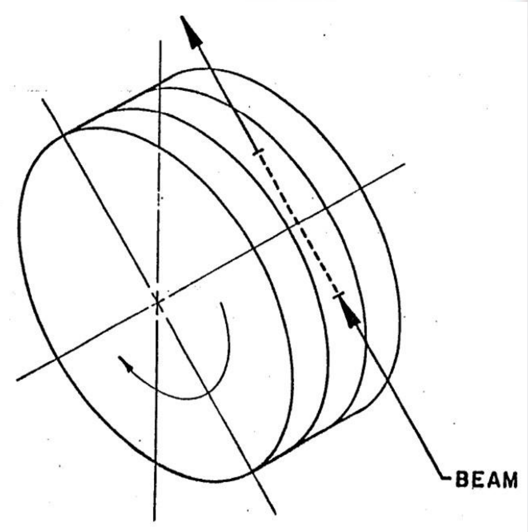
- Production target should produce high yield of pions and muons
- Pion production rates are approximately independent of atomic number, although production of other particles (neutrons, gammas) increases with Z. Low Z materials minimize scattering
- Particle interactions should generate little heat and targets should dissipate heat easily
- Monolithic targets are not necessarily the best design – surface to volume ratio needs to be maximized
- For g-2, we rely on a Inconel 600 based target:

```
material Inconel600 Ni,0.72 Cr,0.15835 Fe,0.10 Mn,0.01 Cu,0.005 Si,0.005 C,0.0015 S,0.00015 density=8.47
```

Target

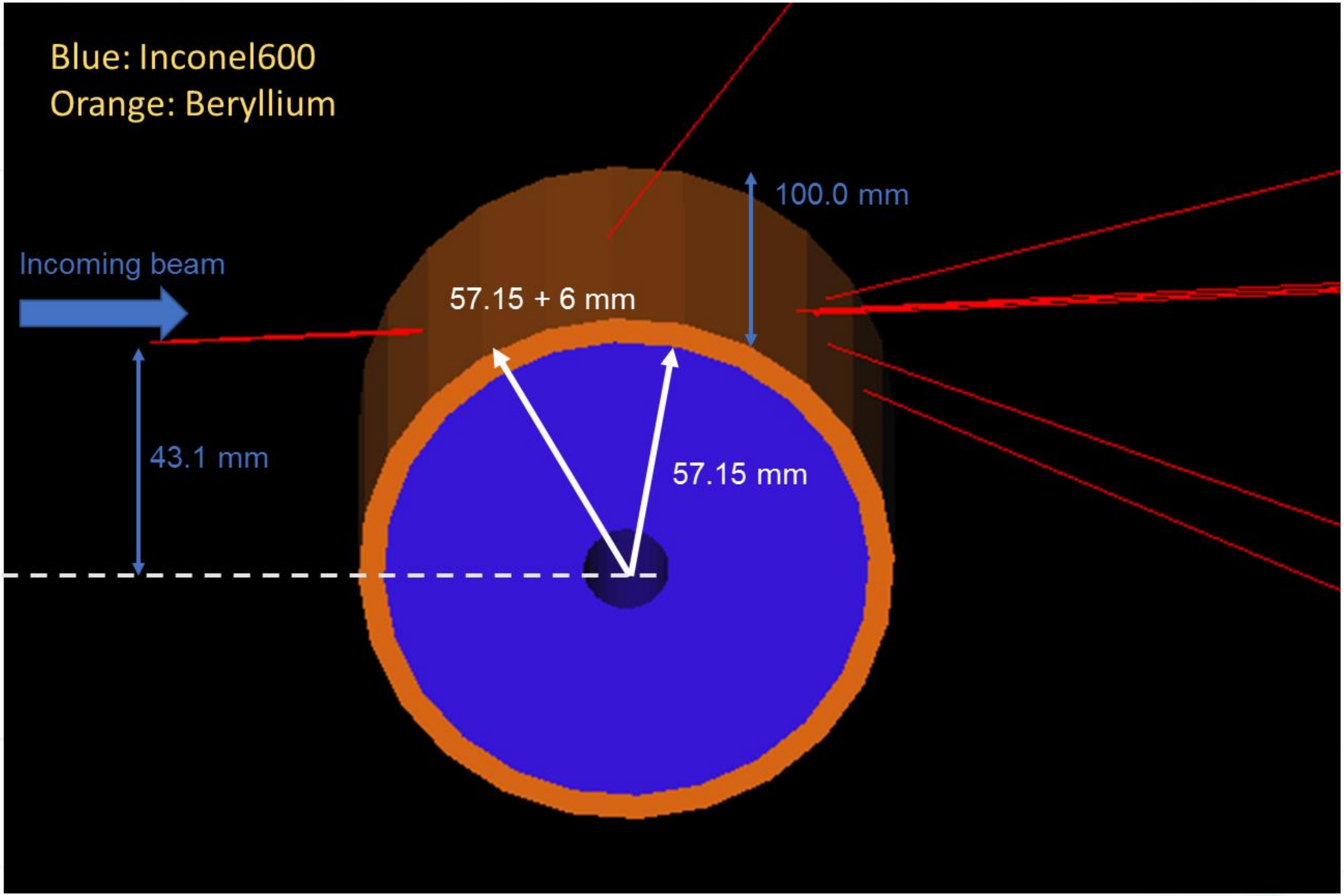




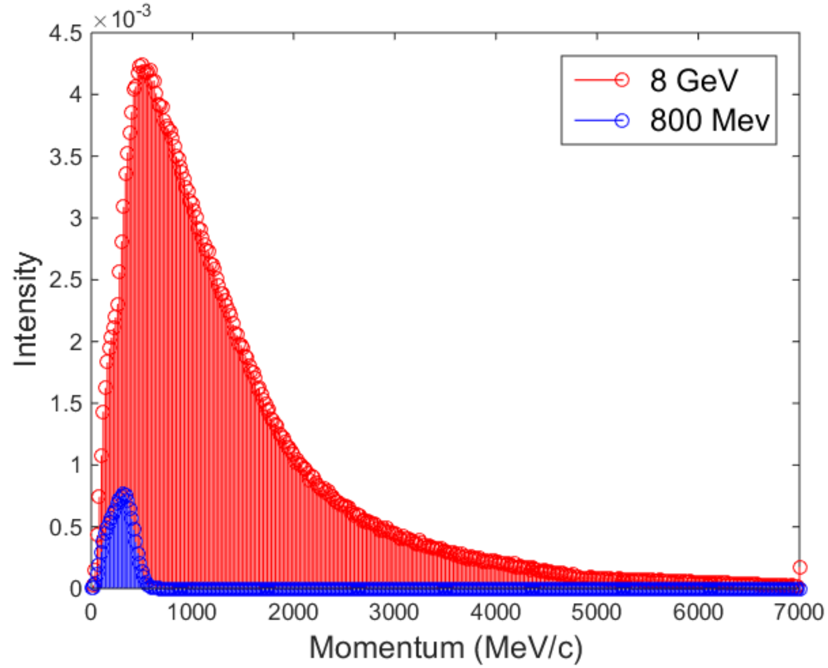


- Target has an outer Be cover to prevent target material from being sputtered onto nearby elements
- Is rotated one turn per 45 s & is moved vertically by 1 mm after each $2x10^{16}$ protons to spread the depletion uniformly

Target model for g-2

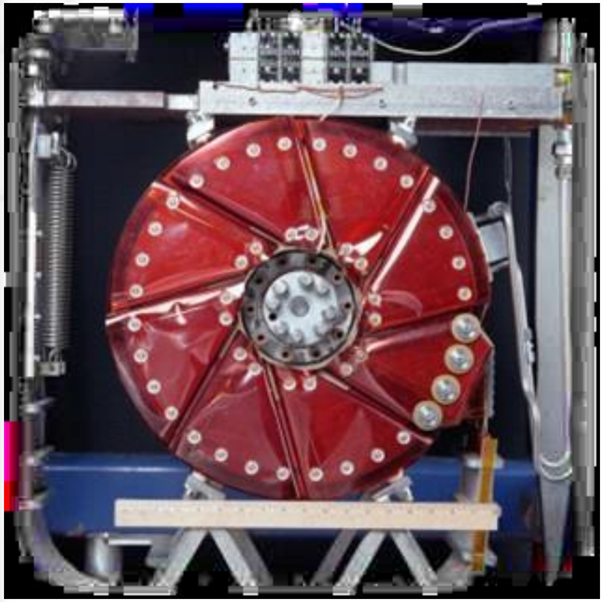


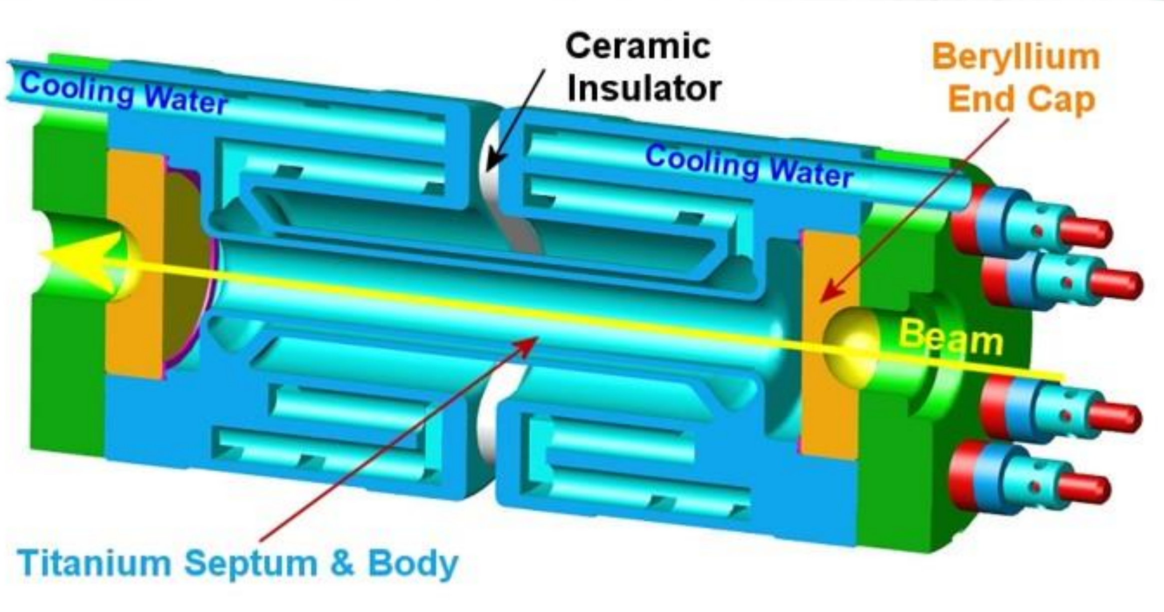
Target & primary beam



- Primary beam properties & target performance are correlated:
  - Number of pions produced is roughly a function of the proton power
  - The higher energy you want, the higher energy protons you need
  - The smaller the spot size, the higher the pion flux

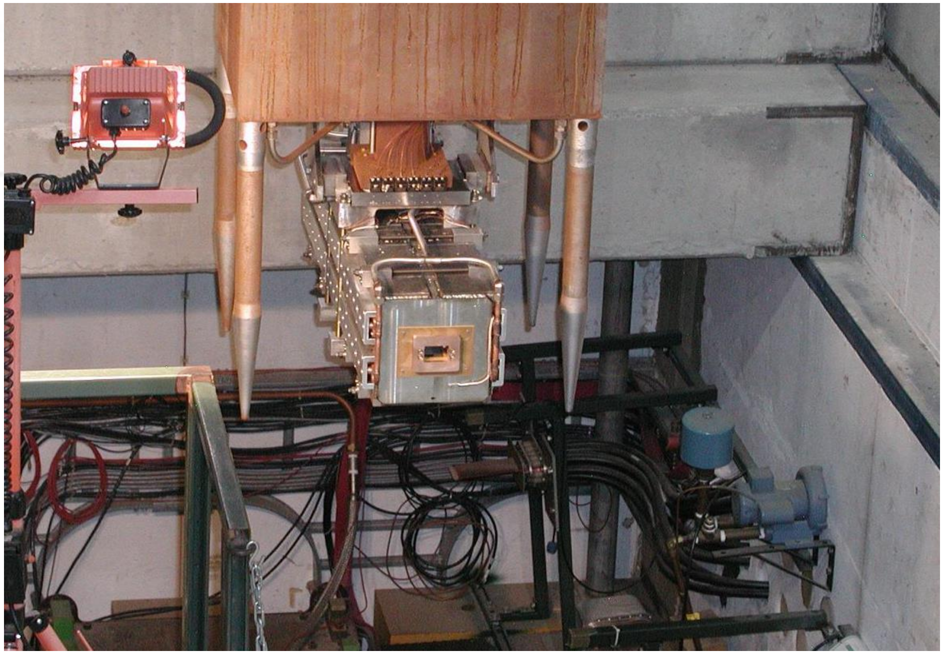
Lithium lens

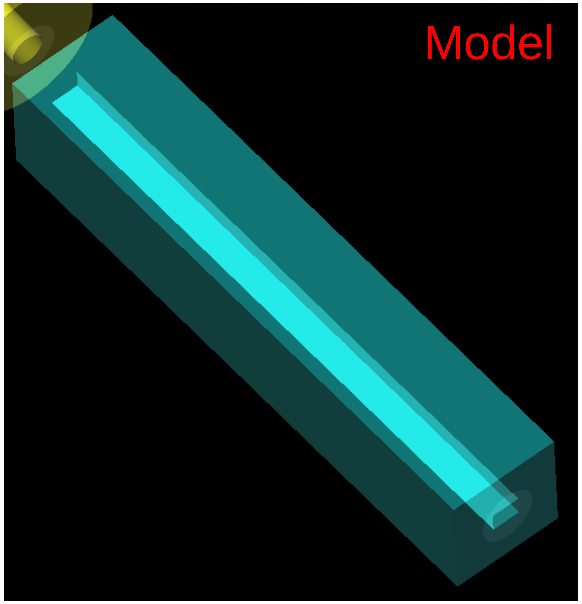




- The lens is a short (16 cm) cylindrical column of lithium metal with a constant current density around its axis giving an azimuthal B-field which focuses particles transversely (both planes)
- Lithium is chosen due to its large interaction length.

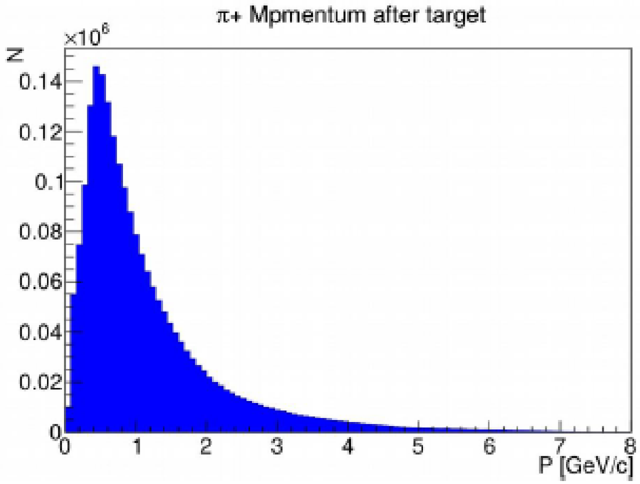
Selection pulsed magnet

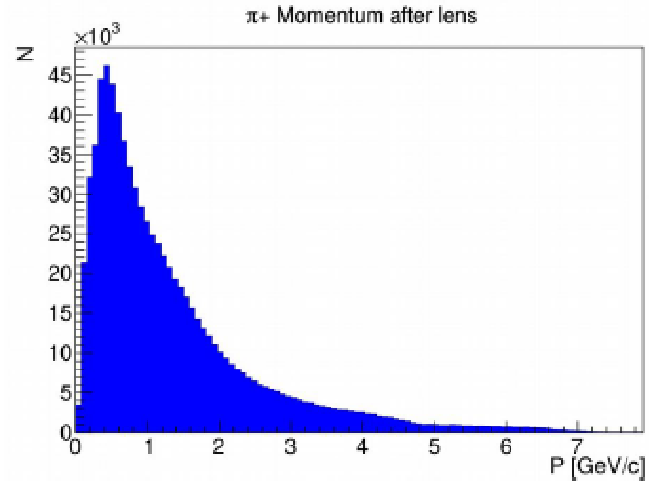


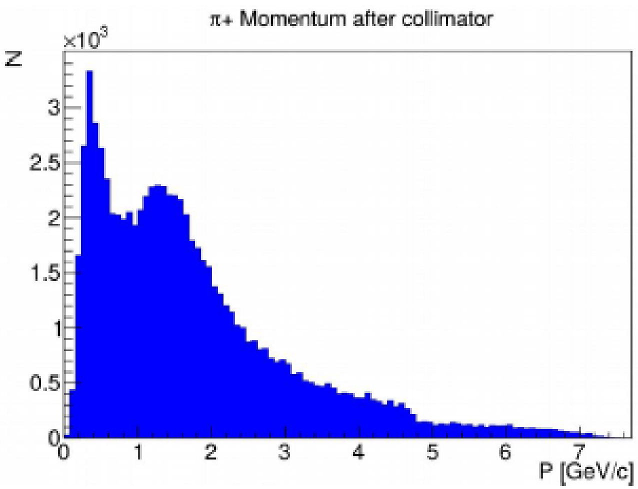


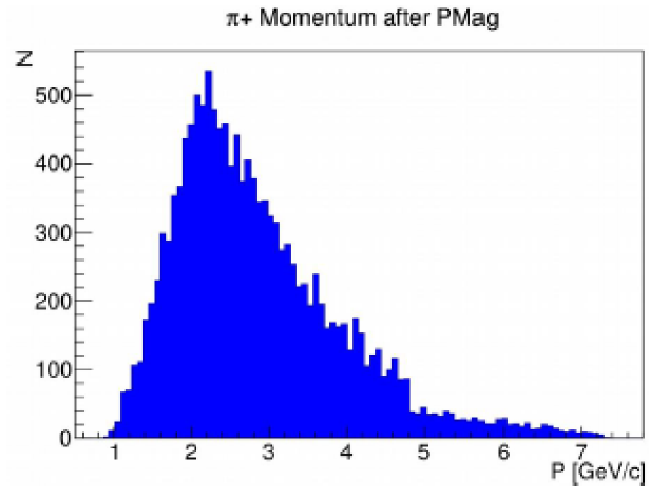
- Is primarily used for momentum selection
- 0.53 T vertical B-field bends particles with 3.1 GeV/c
- Unbent leftover sent to beam dump

Beam simulation through target (1)









Beam simulation through target (2)